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a. REPORT	b. ABSTRACT	c. THIS PAGE			Michael Pursley
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RPPR Final Report
as of 13-Mar-2019

Agency Code:

Proposal Number: 65647NS **Agreement Number: W911NF-15-1-0545**
INVESTIGATOR(S):

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DUNS Number: 042629816 EIN: 576000254
Report Date: 28-Feb-2019 Date Received: 21-Feb-2019
Final Report for Period Beginning 01-Sep-2015 and Ending 30-Nov-2018
Title: Efficient Delivery of Information in Tactical Packet Radio Networks
Begin Performance Period: 01-Sep-2015 **End Performance Period:** 30-Nov-2018
Report Term: 0-Other

Submitted By: Michael Pursley Email: pursley@clemson.edu
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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 4 **STEM Participants:** 4

Major Goals: The major goal was to integrate fountain coding, random linear network coding, multicast transmission strategies, adaptive modulation and channel coding techniques, and network routing methods to provide systems and protocols for the efficient distribution of information throughout a multi-hop tactical packet radio network.

Accomplishments: We devised analytical methods for the design and performance evaluation of protocols for packet-by-packet adaptation of modulation and coding that mitigates the effects of time-varying disturbances on the links of packet radio networks. Statistics are computed during the demodulation of a packet that is received over a radio link. The statistics are employed to provide the control information required to adapt the modulation and coding for the next packet to be sent over the link. The primary advantage of our approach is the avoidance of simulations of the time-varying channel, the adaptation process performed by the protocol, and the generation of the adaptive control information used by the protocol.

We devised new analytical methods for use in the design and evaluation of adaptive transmission protocols that obtain control information from a distance statistic. When employed as the source for control information, distance statistics permit packet-to-packet adaptation of modulation and coding to mitigate the effects of fading, jamming, or other dynamic disturbance on the radio links. Previous investigations of distance statistics have relied on simulation for protocol design and performance evaluation. The primary advantage of our approach is the avoidance of simulations of the time-varying links in the network. In addition, our method also avoids the need simulations of the generation of the adaptive control information and the adaptation process. Among the benefits of our analytical method are valuable insights into the operation of adaptive modulation and channel coding protocols that employ a distance statistic and a tremendous reduction in the computation required in the design and performance evaluations of such protocols.

We developed and evaluated methods for network-coded broadcast distribution of files in tactical multi-hop ad hoc wireless networks that consist of half-duplex packet radios. The methods can be implemented using either fountain coding or random linear network coding. Our approach exploits the broadcast nature of the wireless medium by permitting radios to receive packets from senders other than their designated forwarding radios. The radio links employ adaptive modulation and channel coding that is integrated with the network coding system.

We also investigated the benefits of the integration of fountain-coded broadcast, adaptive modulation and channel coding, and network routing techniques in multi-hop tactical packet radio networks. For such networks, we devised and evaluated five methods for fountain-coded broadcast distribution of a file from a source to multiple destinations.

The methods differ in their use of intermediate nodes, their use of forwarding, and their reliance on a network spanning tree. All five methods employ continued fountain coding to prevent nodes from receiving duplicate fountain-coded packets. We derived an analytical approximation for the throughput of fountain-coded broadcast file distribution in a four-node network with time-varying radio links modeled by independent two-state Markov chains, and we show that our approach to fountain-coded file distribution gives throughput that is very close to the approximation. We employ simulations to examine larger networks in which each radio link has correlated Rayleigh fading and the radios use adaptive modulation and channel coding. For example, we completed a performance evaluation for a 25-node multi-hop packet radio network that accounts for the effects of fading on the radio links and the mitigation of fading provided by adaptive modulation and channel coding.

In very recent work, we described and evaluated a suite of protocols that employ random linear network coding for all-to-all broadcast distribution over time-varying radio links in multi-hop ad hoc wireless networks. All-to-all broadcast distribution requires the delivery of information (e.g., position location information) from each node to every other node. The suite includes a practical protocol for adaptive modulation and channel coding that derives its control information from low-complexity receiver statistics. We provide performance comparisons with an alternative protocol suite. Although we investigate parameter optimization, our emphasis is on robust performance for practical networks in which optimization is not feasible.

Training Opportunities: The PI served as advisor and mentor for two post-doctoral research associates, one graduate student, and two undergraduate students. The senior undergraduate student participated in the ARO URAP program during the summer of 2016 and also conducted ARO-sponsored research during the Fall 2016 and Spring 2017 semesters. The junior undergraduate student participated in the ARO URAP program during the summer of 2017. The graduate student participated in the IEEE Military Communications Conference in 2015, 2016, and 2017.

Results Dissemination: Research presentations were given at the IEEE Military Communications Conference in October 2015, November 2016, October 2017, and October 2018. Presentations were also given at the IEEE Information Theory and Applications Workshop in February 2016 and February 2017. The PI was an invited speaker at the University of Florida in October 2015.

Honors and Awards: Patrick Dynes graduated Summa Cum Laude and with Electrical and Computer Engineering Departmental Honors in May 2017. He received the Mathematical Sciences Faculty Senior Award and the Outstanding Senior Award in the Sciences.

Siddhartha Borkotoky received the 2017 Clemson University John J. Komo Graduate Research Award in Communication Systems and Networks.

Michael Pursley received the IEEE Communication Theory Technical Achievement Award in May 2018.

Protocol Activity Status:

Technology Transfer: Michael Pursley served as a member of the Naval Research Laboratory Information Technology S&T External Review Panel during July 18-20, 2016. He was the lead panel member for NRL research in Communications and Networks. He has received an informal invitation to serve on the NRL Information Technology S&T External Review Panel later this year.

Interactions have continued with SPAWAR-Pacific, SPAWAR-Atlantic, and MIT Lincoln Laboratory.

Postdoctoral Research Associate Michael Dowling joined MIT Lincoln Laboratory in September 2016.

PARTICIPANTS:

Participant Type: PD/PI
Participant: Michael Pursley
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:

National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Siddhartha Borkotoky
Person Months Worked: 5.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Undergraduate Student
Participant: Patrick Dynes
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Undergraduate Student
Participant: Matthew Dierksheide
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Michael Dowling
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Siddhartha Borkotoky
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

CONFERENCE PAPERS:

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Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: IEEE Military Communications Conference
Date Received: 27-Jul-2016 Conference Date: 26-Oct-2015 Date Published: 26-Oct-2015
Conference Location: Tampa, FL
Paper Title: Broadcast File Distribution in a Four-Node Packet Radio Network With Network Coding and Code-Modulation Adaptation
Authors: Siddhartha Borkotoky, Michael Pursley
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: IEEE Information Theory and Applications Workshop
Date Received: 27-Jul-2016 Conference Date: 02-Feb-2016 Date Published: 02-Feb-2016
Conference Location: San Diego, CA
Paper Title: Network-coded file distribution in an ad hoc relay network
Authors: Siddhartha Borkotoky, Michael Pursley
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2016 IEEE Military Communications Conference
Date Received: 21-Feb-2019 Conference Date: 01-Nov-2016 Date Published: 01-Nov-2016
Conference Location: Baltimore, MD
Paper Title: A Method for Network-Coded Broadcast in an Ad Hoc Network
Authors: Siddhartha Borkotoky, Michael Pursley
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2017 IEEE Information Theory and Applications Workshop
Date Received: 21-Feb-2019 Conference Date: 13-Feb-2017 Date Published: 13-Feb-2017
Conference Location: San Diego, CA
Paper Title: A comparison of two methods for fountain-coded file distribution in an ad hoc network with relays
Authors: S. S. Borkotoky, M. B. Pursley
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2017 IEEE Military Communications Conference (MILCOM)
Date Received: 21-Feb-2019 Conference Date: 23-Oct-2017 Date Published: 21-Oct-2018
Conference Location: Baltimore, MD
Paper Title: A comparison of three adaptive transmission protocols for fountain-coded multicast
Authors: Siddhartha Borkotoky, Patrick Dynes, Michael Pursley
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2018 IEEE Military Communications Conference (MILCOM)
Date Received: 21-Feb-2019 Conference Date: 29-Oct-2018 Date Published: 29-Oct-2018
Conference Location: Los Angeles, CA, USA
Paper Title: Fountain-Coded Multicast in Tactical Packet Radio Networks: Throughput Improvements Provided by Relay Nodes
Authors: Siddhartha Borkotoky, Michael Pursley
Acknowledged Federal Support: **Y**

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Publication Type: Thesis or Dissertation
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Date Received: 20-Aug-2017 Completion Date: 8/4/17 6:14PM
Title: Network Coding in Tactical Packet Radio Networks with Time-Slotted Channel (2017 URAP Report)
Authors: Matthew Dierksheide
Acknowledged Federal Support: **Y**

Publication Type: Thesis or Dissertation
Institution: Clemson University
Date Received: 21-Feb-2019 Completion Date: 8/4/17 10:14PM
Title: Network Coding in Tactical Packet Radio Networks with Time-Slotted Channel (2017 URAP Report)
Authors: Matthew Dierksheide
Acknowledged Federal Support: **Y**

Publication Type: Thesis or Dissertation
Institution: Clemson University
Date Received: 20-Aug-2017 Completion Date: 4/26/17 4:00AM
Title: Network Coding for Packet Radio Networks
Authors: Siddhartha Borkotoky
Acknowledged Federal Support: **Y**

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Institution: Clemson University
Date Received: 21-Feb-2019 Completion Date: 4/26/17 12:00PM
Title: Network Coding for Packet Radio Networks
Authors: Siddhartha Borkotoky
Acknowledged Federal Support: **Y**

Nothing to report in the uploaded pdf (see accomplishments).